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Research Paper

Research on the heat and mass transfer characteristics of fin-tube exchanger under low pressure environment

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HIGHLIGHTS

- The mass transfer process is greatly infected by low pressure in wet condition.
- The performance parameters have different variation in low-pressure environment.
- The boundary layer is the main cause for the change of evaporator performance.
- The main forms of heat transfer in different fin sections are different.

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ABSTRACT

China has rapidly developed in recent years, with highlands (for example, the Qinghai-Tibet Plateau, with average altitude over 4000 m, the environmental pressure is less than 60 kPa) being increasingly utilized; leading to a greater application of the heat exchanger due to the need to deal with low pressure environments of the higher altitudes. This paper focuses on the heat transfer and flow characteristics of a plate-fin heat exchanger under low pressure environment and wet condition. By means of theoretical analysis, the main performance parameters changing with the environmental pressure in the air side of heat exchanger were derived, and the performance of a plate fin heat exchanger was tested under low pressure and humidity conditions on the test bench. The results indicate that the heat transfer performance of heat exchanger decreased with the decrease of environmental pressure under wet condition. Compared with that under the atmospheric pressure condition, the latent heat transfer and mass exchange of the plate-fin heat exchanger had reduced by about 65.1% and 65.6% respectively at 61 kPa condition. To explore the mechanism of how low-pressure working on the latent heat transfer and flow characteristics of heat exchangers, the heat transfer and flow process of heat exchanger under low pressure and humidity conditions were simulated. The results showed that the performance decline of heat exchanger was closely related to the dramatic changes of mass transfer process and concentration boundary layer under low pressure environment.

1. Introduction

Heat exchanger is the core component of air-conditioning system, and its performance has a direct and fundamental impact on the working state of the whole system [1]. As such, the technology responsible for ensuring quality performance of the heat exchanger in any environment is valuable and important. Existing studies and experiences indicate that air conditioning systems face a series of technical problems when used in plateau environments. These problems, including inadequate refrigeration, efficiency decrease and noise increase, etc. [2–4], affect the normal operation of heat exchangers seriously. There is no doubt that all these problems are closely related with the performance change of heat exchanger, and it is therefore imperative to study the mechanisms of how low pressure environments impact on the performance of heat exchanger.

At present, there have been some research papers on the relevant aspects of this topic, the heat and mass transfer characteristics of heat exchanger under wet conditions is still a hot research topic. Zhou [5] studied the heat and mass transfer characteristics on the air side of flat fin tube under wet condition. The results of simulation showed that the sensible heat transfer coefficient of flat fin under wet condition is similar to the heat transfer coefficient under dry condition, but the total heat transfer coefficient is much larger than that under the dry condition. Yang [6] focuses on the topic of

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Nomenclature

c_p	specific heat [J/(kg K)]
d	moisture content (g/kg air)
d_n	Air moisture content at measuring point (kg/kg air)
D_{AB}	diffusion coefficient (m^2/s)
h	enthalpy of humid air (J/kg)
M	Molar mass (g/mol)
m_w	mass exchange quality (kg/s)
P	atmospheric pressure (Pa)
P_v	water vapor pressure (Pa)
P_s	saturation water vapor pressure in the fin tube surface (Pa)
Q	latent heat exchange (kW)
q_v	volume flow (m^3/s)
q_m	mass flow (kg/s)
q_H	the latent heat value under H meters high (J/kg)
R	gas constant [J/(K mol)]
Re	reynolds number
Sc	schmidt number
T	temperature (°C)
Δt	temperature difference (°C)
ν	kinematic viscosity (m^2/s)
v_n	Air specific volume at measuring point (m^3/kg)

Greek letters

α_D	mass transfer coefficient (m/s)
δ_c'	the effective concentration boundary layer thickness (m)
δ	flow boundary layer thickness (m)
δ_c	the concentration boundary layer thickness (m)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)

Subscript

H	at H m high altitude
0	at sea surface height
i	inlet
o	outlet

the heat exchanger performance inflected by the inlet uneven wet-air under wet condition. The study indicates that the deviation of sensible heat transfer caused by uneven speed increases with the increase of inlet relative humidity, but the deviation of latent heat transfer and total heat transfer decreases with the increase of inlet relative humidity. Weng et al. [7] built a numerical model of droplet formation, growth and movement characteristics inside the foam metal based on classical theory of heat and mass transfer. The heat and mass transfer characteristics of wet air are calculated by the model, the comparison between computing results and experimental results proved that the model has high accuracy. Meanwhile, Xu et al. [8] carried out an experimental study on this process. The results show that the relative humidity, temperature, and velocity of the inlet air have a great impact on the heat and mass transfer characteristics of foam metal under wet condition, and the influence of air temperature is greatest. Yang et al. [9] established a model for the formation and movement of condensation water droplets on the fin surface, which has good accuracy and less error.

Most of the above researches are under normal pressure (1 atm) condition. At present, there is little special research on this topic under low pressure and wet condition, and current researches often consider the whole system as the research object. Refs. [10–13] studied the operation status and control strategy of vehicle air-conditioning system in plateau environment. Among them, Li et al. [12] put forward a control scheme of air conditioning system based on the comfort of vehicle passengers. This scheme considers the human body, indoor environment, outdoor air pressure, oxygen concentration inside the car and other factors, which aim to realize the unity of comfort and energy saving. Hader et al. [13] tested the change of the cooling capacity of direct evaporative air conditioner under different pressures, with results indicates that the cooling capacity of air conditioning system has been decreased under low pressure environment. However, due to that the mechanism of low pressure environment working on the air conditioning system is complicated, there is no complete theoretical explanation at present. In addition, there have been some corresponding correction standards and methods [14,15] at home and abroad to deal with the design and use of heat exchanger under negative pressures. However, these methods can only be used for the simple design of heat exchanger, and the accuracy and applicability of them are hard to guarantee. In light of the above review on current research findings, it is not difficult to see that in-depth research on this particular topic is still relatively scarce, meaning that we have yet to fully uncover the mechanisms of how the low-pressure environment working on the heat transfer and flow characteristics of heat exchangers. Accordingly, more research on this topic should be encouraged.

This paper focuses on the heat transfer and flow characteristics under low pressure environment and wet condition. In this study, a bench test method is applied to test the heat transfer and flow characteristics of heat exchanger under different pressures and wet conditions. In addition, the mechanism of low-pressure environment working on the heat transfer and flow characteristic under wet conditions was carried out by theoretical research, and the working process was calculated by means of numerical simulation.

2. Theoretical research

Under the refrigerate condition, the evaporation temperature of the heat exchanger is lower than the dew-point temperature of moist air, so the heat exchanger is in the wet condition, and the moist air is in the cooling and dehumidifying process. In addition, the latent heat exchange process is actually the mass transfer process between the wet air and the cold fin-tube surface. During the process, moisture in wet air will diffuse to the fin-tube surface and condense into water droplets. The heat of condensation and absorption from water is just the latent heat exchange. Its formula [16] is:

$$Q = m_w q_H \tag{1}$$

The latent heat value of steam under different pressure is shown in Table 1.

It can be seen from Table 1 that the latent heat value changes slightly with the environmental pressure, so it can be seen as a constant value. Therefore the main effective variable of low pressure working on the latent heat transfer process is mass transfer rate. According to information gathered from past experiences, the flow velocity between fins of the heat exchanger used in the air conditioning system mostly vary in the range of 0–15 m/s